Advancements in MEMS Materials and Processing Technology

John D. Olivas and Stephen Bolin

From achievements in display imaging to air bag deployment, microelectromechanical systems are becoming more commonplace in everyday life. With an abundance of opportunities for innovative R&D in the field, the research trends are not only directed toward novel sensor and actuator development, but also toward further miniaturization, specifically achieving micro- and nanoscaled integrated systems. R&D efforts in space, military, and commercial applications are directing specific research programs focused on the area of materials science as an enabling technology to be exploited by researchers and to further push the envelope of micrometer-scaled device technology. These endeavors are making significant progress in bringing this aspect of the microelectro-mechanical field to maturation through advances in materials and processing technologies.

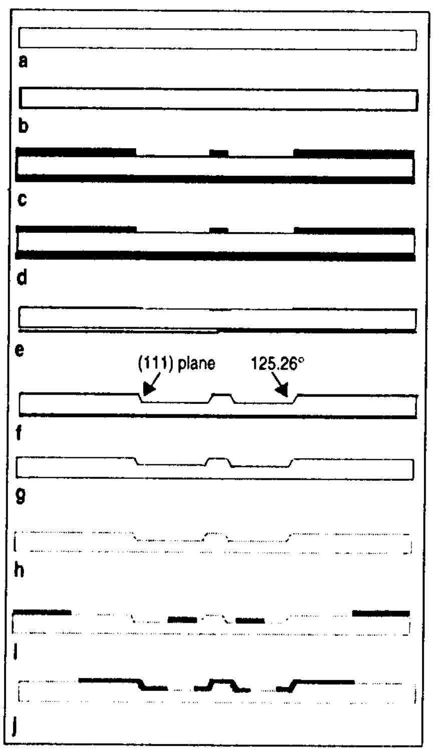


Figure 1. An example of bulk micromachining. (a) bare silicon substrate; (b) deposit silicon nitride on both sides of substrate; (c) deposit and pattern photoresist; (d) silicon nitride etch; (e) remove photoresist; (f) anisotropic silicon etch; (g) remove nitride; (h) grow thermal oxide; (i) deposit and pattern photoresist; and (j) deposit metal and lift off photoresist.

INTRODUCTION

Microelectromechanical systems (MEMS) are typically defined as a class of mechanical actuators, sensors, and other devices that are microscopic in scale and typically fabricated by the techniques used in the manufacture of integrated circuits and semiconductor components. In general, the devices operate under the same premise as macroscale components; however, fundamental principles, from design and materials selection to fabrication techniques, are substantially different. The devices may either be independent structures or be integrated into other microelectronic circuit devices.[1]

Traditional design principles that govern how engineers and scientists create devices take on a significantly different twist in the world of MEMS.[2] As an example, issues such as friction, surface tension, static electricity, residual stress, etc., play a more dominant role in device operation than forces such as gravity. Whereas designers would have never dreamed of supporting a sandbag-sized mass on the end of a car antenna, designing at the micrometer and submicrometer scale makes these aspect ratio mismatches less of an issue. In fact, many devices take advantage of this type of configuration as a fundamental basis for their operation.[3] Additionally, the cost of materials and fabrication tend to be minimal when compared with items such as facilities costs and research time.

Microfabrication and micromachining have their origins in efforts beginning in the mid-1960s through early 1970s. Investigations at Case Western Reserve, the University of California at Berkeley, the University of Wisconsin, the Massachusetts Institute of Technology, and the University of Michigan followed the lead of Stanford University in the fabrication of the first micromachined sensor. Although academia has been the leader in the development of the field for a number of years, it has only been since the breakthroughs in the mid-1980s by the University of California at Berkeley and the University of Wisconsin that the fabrication tools needed for a wide array of geometries and structures could be realized with silicon.

MEMS devices have achieved commercial applications on a number of fronts.[4] While not trying to capture all manufacturers or devices, several commercial activities actively involved in MEMS development are worth mentioning.[5] Texas Instruments' digital mirror devices are arrayed micrometer-scale mirrors used to produce high-definition projection images in gray scale and full color. Accelerometers that trigger air bag deployment in automobile crashes are being manufactured by Analog Devices and Lucas Nova Sensor. Fluid transistors using microchannel technology have been developed by Redwood Microsystems for integrated fluidic circuitry, with functionality similar to electronic circuitry devices. Honeywell has developed infrared cameras comprising infrared sensitive detectors manufactured using MEMS technology. Lawrence Livermore National Laboratory has also developed weapons-arming accelerometers, heat dissipaters, and thermopneumatic pumps. Principally constructed of metallized silicon, single and polycrystalline, these devices are fabricated by a variety of techniques to create both simple and complex geometry.[6]

Clearly the number of potential appli-

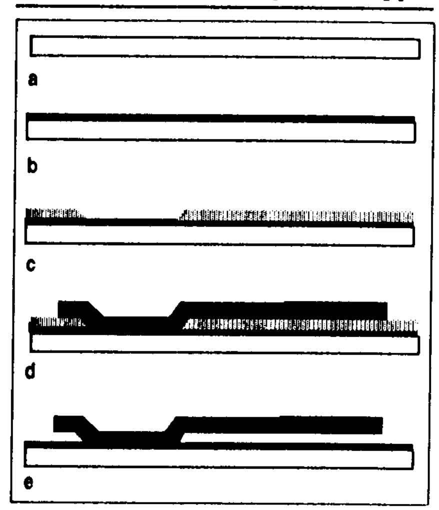
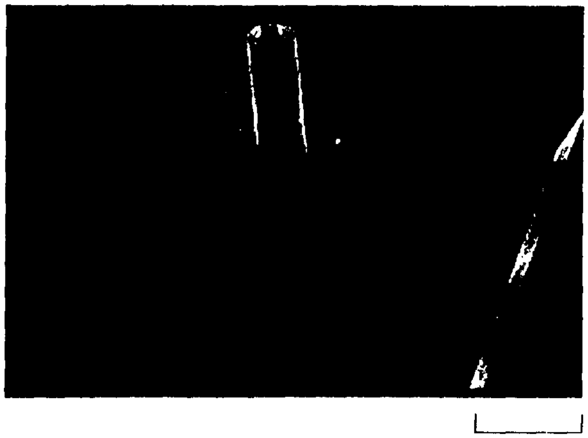


Figure 2. An example of surface micromachining. (a) bare silicon substrate; (b) deposit boron-doped polysilicon layer; (c) deposit and pattern sacrificial pattern of phosphosilicate glass (PSG); (d) deposit and pattern structural polysilicon; (e) etch away PSG to release polysilicon cantilever.

cations far outweigh the current state of technology. Limited only by imagination, these innovators extend concepts of their MEMS devices to novel applications. Automobile tires are one day envisioned to have embedded miniaturized pressure sensors that could ultimately lead to a ten percent savings in oil imports by assuring proper tire pressure. Inertial guidance systems could be used in "dumb" munitions, thereby improving accuracy leading to reductions in the number of weapons needed to destroy a target and the necessary stockpile. In-situ monitoring is proposed to be embedded into vehicle components (e.g., skin, engine, frame, fuel system, etc.), whereby temperature, pressure, stress, and other performance characteristics can be observed to establish the history and relative health of vehicles used in air, space, and sea.[7] Even further, the provision of stealth characteristics and improved aircraft performance is considered feasible through the incorporation of miniature sensors and actuators controlling minuscule variations in aerodynamic profile for minimizing boundary-layer turbulence. Entire vehicle development is also seen as plausible, a possible example being a centimeter-size submarine, remotely controlled, that could be used to inspect and repair damage in toxic pipe lines. Perhaps even smaller vessels will one day be used to journey through your veins and arteries, removing plaque or diagnosing disease. With advances being made in materials development and processing, these ideas are coming closer to reality.

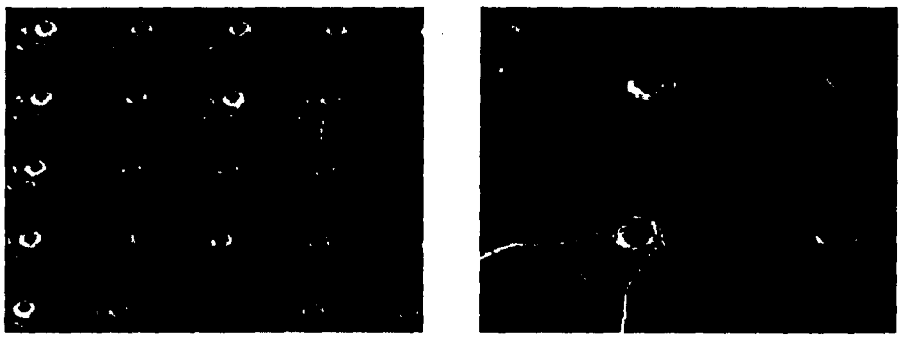
MEMS DEVICES

To fully understand the developments of and challenges to the materials-science field in the present day and future world of MEMS, it is important to appreciate the development of this field and its current state of technology. Although a number of processes and a variety of other components can arguably fit into the realm of MEMS, this discussion focuses on sensors and actuators.



1 mm

A micromachined vibratory gyroscope fabricated at the Jet Propulsion Laboratory. The machine is scheduled for flight on NASA's X-33 mission.



Micromachined components of a Texas Instruments projection system. Each device controls the reflection of light to create one pixel in the projected display.

Sensors

MEMS sensors belong to a class of devices that convert nonelectric inputs (such as temperature, pressure, acceleration, fluid flow, etc.) to an electrical signal. Although many devices and materials currently available are capable of this conversion, fabrication using microelectronics technology allows for many attractive distinctions. Because the technology is capable of manufacturing on scales from centimeters to nanometers, device sizes, weights, and power requirements can be reduced dramatically.[8] Additionally, reduced mass, damping, and complexity lead to devices that are capable of greater sensitivity than their macroscaled counterparts. The wide array of sensing configurations, materials selection, and fabrication processes provide designers with a multitude of design options. As the technology has evolved, materials science is playing an ever-increasing role in the continuing development of the field. Sensors that have been developed and demonstrated include those used to monitor pressure, acceleration, seismic activity, gas species, temperature, optical features, position, fluid flow, and many other physical inputs; all are dependent on material selection and fabrication methods.

Many sensors operate by monitoring the displacement of elements such as membranes, beams, diaphragms, or hinged masses. These elements are fabricated using a number of techniques,

Table I. Typical MEMS Processes and Techniques

Processes	Techniques	Examples of Applications
Etching	Isotropic, anisotropic, dopant stop	Pyramidal tunneling tip, microchannel, beams, diaphragms, bridges
Lithography	UV photo, e-beam, x-ray (synchrotron)	Deep channeling, mold formation
Thin-Film Deposition	Sputtering, CVD, PVD, electron, vapor, sublimation	Electrode formation, formation of active and passive coatings
Thick-Film Coating	Sputtering, CVD, PVD, electron, vapor, sublimation	Bonding pad formation
Electrosurfacing	Anodizing, plating, chemical/mechanical polishing	Creation of metallic structures
Microcutting	Laser, e-beam, EDM, ion beam	Production of larger structures
Wire Bonding	Ultrasonic, thermocompression	Electrical I/Os
Interfacial Bonding	Adhesives, thermal, friction, diffusion, eutectic, thermal compression, brazing	Production of multisubstrate-bonded MEMS structures
Surface Alteration	Ion milling, diffusion	Custom fabrication and prototyping of MEMS devices

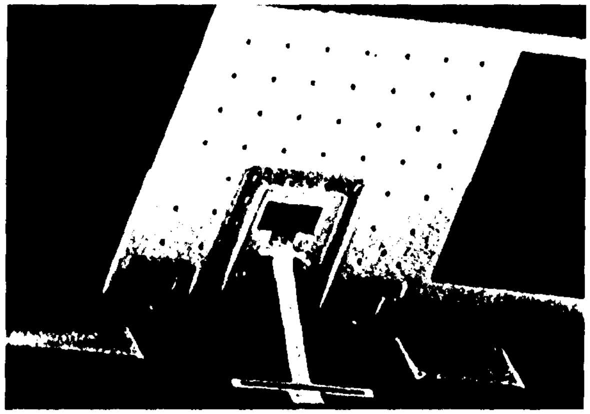
UV—ultraviolet, CVD—chemical vapor deposition, PVD—physical vapor deposition, EDM—electrical discharge machining, e-beam—electron beam including isotropic/anisotropic etching, high-temperature fusion bonding or deposition, and subsequent support removal. Perhaps the most widely used, if not widely known, of these sensor types are the cantilevered capacitive accelerometers. Capacitive devices operate on the fundamental principles of interdigitated plate or beam structures that form a differential capacitor. As these structures are subjected to force and are displaced, the capacitance is measured across the structure. They are typically mounted on a movable mass, and fixed electrodes are anchored onto the substrate. Although many displacement-sensitive devices operate on the principle of capacitive sensing, sensors using electron tunneling, magnetoresistance, structural resonance, piezoresistive, and conventional piezoelectric materials have also been demonstrated as capable of rivaling device performance.

Inertial position sensors are fabricated from silicon and operate by transferring the energy of a Coriolis-type effect acting on the device to one of several types of sensors.[9] In one case, the force acts on a dithered pair of precision accelerometers. In another case, a doubly gimbaled cloverleaf structure, operating in torsional vibration mode, transfers the effect into orthogonal torsional vibration, which is then correlated to the rate of rotation.

A variation on the accelerometer is the MEMS hydrophone, which uses electron tunneling as a sensing mechanism. This device, fabricated by bulk micromachining, utilizes a preferentially etched and metallized pyramidal silicon tip on a single-crystal silicon substrate. By placing a thin silicon beam within close proximity (one nanometer) to the tip, electron tunneling can be established.[10] As the beam is acoustically excited and moves closer or further away from the tunneling tip, varying the voltage such that the tunneling current is maintained allows for very precise acoustic measurement at a fraction of the mass of conventional systems.

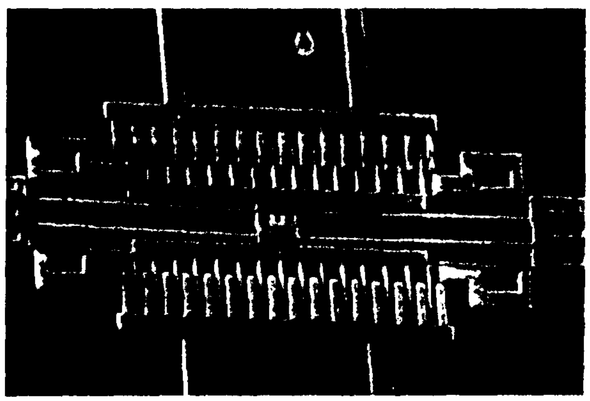
In addition to having excellent mechanical-response characteristics, silicon-based devices are also sensitive to other forms of energy. Optics technology and MEMS devices are being integrated to realize optical measurement by means of microscaled Fabry-Perot interferometers.[11] Resonant-beam strain sensors have also demonstrated photon sensitivity through the measurement of vibrational motion.[12] Clearly, achievements using this fabrication technology are limited only by materials properties and current understanding of these properties (the latter is the primary limiting factor).

The cadre of sensing configurations, materials selection, and fabrication processes provides designers with a multitude of design options. As the technology continues to evolve, materials science will continue to play an ever-increasing role in the promotion of the field. This technology is key to providing the support necessary to allow the field to continue its growth and for even more complex designs to be realized.



20 µm

An example of a locking mechanism fabricated at UCLA using MEMS fabrication technology.



10 µm

A typical MEMS vibrating comb mechanism. The device senses a capacitance change between the comb teeth, and the sensor is subjected to acceleration.

Actuators

Unlike MEMS sensors, which utilize an external force to produce a motion in the MEMS device (this motion, in turn, produces an electrical signal), MEMS actuators take an electrical input and convert it into motion. In most cases, the motion or actuation itself is not the sought end product, but rather a necessary functionality. MEMS actuator motion may be either continuous motion (e.g., micromotor or turbine), a motion that is repeated within a narrow range (e.g., switch or optical deflectors), or a one-time motion in which an object is drawn into a locked position (e.g., precision assembly).

Microscopic electric motors fabricated of silicon and micrometer-scale wires were among the earliest MEMS devices created. Unfortunately, when such devices, which work well on the macrolevel, were scaled down, it was found that the mechanical power created was insufficient to overcome the internal friction of the device and still produce useful work. In order to work around this deficiency, motors have been developed that utilize magnetic levitation to produce a frictionless motor. Such a micromotor was described[13] where an arrangement of stator and rotor coils both levitated the rotor and provided power for it to spin. Even with friction absent, the motor had several deficiencies, perhaps the greatest of which was that it had to remain in an upright position as the force of gravity balanced the levitation force. While it would be possible to redesign the motor to have the levitation force balanced by another repulsive force placed above the rotor, this would make access to the potential work output of the motor essentially impossible.

Other electrically developed forces have proven to be extremely useful on the microscale. The two most notable methods of supplying power are electrostatics and piezoelectric (PZT) actuators.

Electrostatic forces have proven to be an extremely useful method to produce motion in a wide variety of MEMS devices. Typical designs balance the elasticity of the device material against the electrostatic force created by two adjacent charged electrodes. Because the spacing involved between electrodes is extremely small in a MEMS device, the electric field generated can be very high and the force great even though a relatively small potential is applied to the electrodes.

Sandia National Laboratories[14] has produced a complete surface micromachined microengine. The device converts linear motion, produced by an arrangement of linear electrostatic comb actuators, into rotary motion. This is accomplished in much the same way an automobile engine converts the linear motion of the pistons into the rotary motion of the driveshaft and wheels. Comb actuators consist of parallel arrays of electrodes arranged like interweaving teeth of two combs; one array is fixed in position, the other has freedom of motion. By applying alternating potential to the arrays, the movable one undergoes a repeated back-and-forth linear translation.

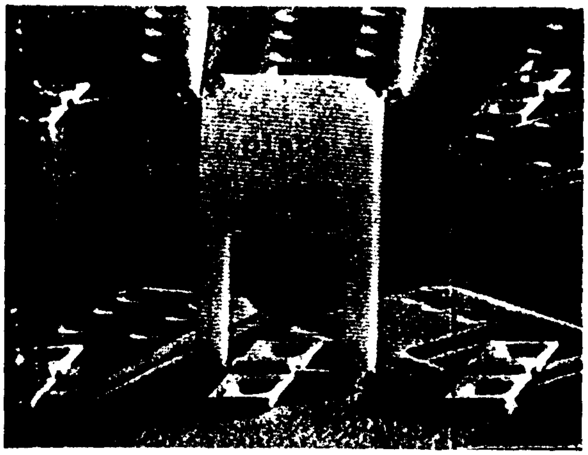
Micropumps are among the devices of interest to a number of investigators because of their broad range of potential application in systems ranging from micromass spectrometers to cold-gas microthrusters for new generations of microspacecraft. An electrostatically driven diaphragm pump has been fashioned using bulk microma-chining of silicon.[15] The application of potential to metal films deposited on the diaphragm and a stationary counter electrode draws fluid into the pump chamber through an inlet orifice. When the voltage is removed, the diaphragm springs back to its relaxed position and forces the fluid through the outlet orifice. Precision micromachined flap valves alternately seal each orifice, thus preventing backflow.

Researchers at Stanford University described an electrostatically actuated ciliary microactuator array for object manipulation.[16] The devices contain an arrangement of independent thermal and electrostatic actuators fabricated from polyimide. Their design allows for independent actuation of each element and features high lifting capacity and large angle deflection with a low power hold-down mode. Capacitive sensing of actuator position allows for feedback control and object sensing.

Several investigators have worked at developing micrograppers. These have typically been fabricated from silicon and either electrostatically or thermally driven. However, these devices typically remain attached to the substrate, giving them limited usefulness. For example, micrograppers have been fabricated using the Lithographie Galvanoformung Abformung (LIGA) technique.[17] The devices built up in this manner are made from electroformed nickel.

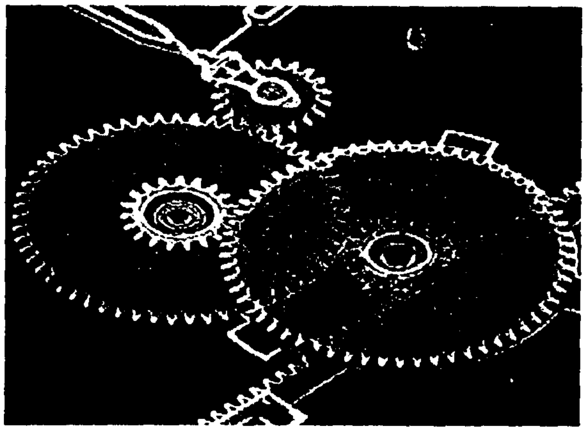
Arrangements of piezoelectric crystals or ceramics can also provide motion to actuators in the same manner as electrostatic drives. The authors of the Sandia microengine described above noted in their article that PZT actuators could be directly substituted for the electrostatic combs. A unique variation of the PZT actuator was described, in which a multilayer pillar of PZT cells is energized over only a portion of its cross section.[18] As a result, the pillar is bent as that section of the cells expands in response to the applied voltage. Actuators using this technology are envisioned for use in a variety of applications, including an inchworm mechanism, microfingers for micromanipulators, and direction control of microoptics.

A variety of thermally powered sources of motion have also been demonstrated with MEMS devices. One example is the use of shape memory alloys (SMAs). SMAs have been used for the microactuation of an implantable drug-delivery system.[19] In operation, constant pressure is kept on the drug reservoir. A calibrated flow channel is placed between the reservoir and a controlling valve. The valve is opened when the SMA is heated and closes again when the heat is removed. Because SMAs achieve their motion from a change in the crystal structure of the metal, the force they exert is extremely high, thus producing a very reliable and repeatable operation.



5 µm

Erectile surface micromachined components fabricated at UCLA showing the details of the staple/hinge mechanism.



100 µm

Details of a microengine produced at Sandia National Laboratory.

In another application of SMAs, researchers at Lawrence Livermore Laboratory have described their use of SMAs in the fabrication of a microgripper[20] to be used in such applications as fine alignment eutectic bonding and a variety of medical applications such as microbiopsy and endovascular therapy. Again, the large gripping forces obtainable from the SMA make these applications feasible. The SMA is capable of generating actuation stresses as high as 500 MPa at the transformation temperature.

It has been pointed out that in scaling down devices, the response time of an SMA can be greatly improved due to the decrease in thermal mass.[21] It is possible to have SMA-powered actuators that function at rates in excess of 30 Hz.

Considerable work in the field of microoptics has been performed at the University of California at Los Angeles (UCLA). A recent paper by UCLA researchers describes the application of micromachining to the production of numerous microoptical components, which are integrated into complete optical systems.[22] Included are a variety of micropositioners, such as rotary stages and linear translation stages. A unique development that makes high-aspect microoptical systems possible is the microhinge technology developed at UCLA. In this technology, polysilicon members, which will become standing optical elements, are fabricated in a horizontal position using surface micromachining technology. At the same time, a polysilicon staple is fabricated that extends through edge openings in the optical members and joins with the silicon substrate.

When the phosphate glass on which the optical member and staple have been grown is etched away, the optical member can be folded up from the single-crystal silicon substrate surface and is held in place by the staple. Adjacent members can be fabricated that will, when folded up, serve to secure the optical member in place, much like folding up a cardboard cutout.

It must be emphasized that while electrostatics, PZTs, and SMAs are the primary mechanisms for providing power for the operation of actuators, they are far from the only mechanisms. Virtually any physical phenomena that can produce motion can and probably has been used to actuate a MEMS device. Some are magnetostriction,[23] vacuum,[24] and the boiling of liquids.[25]

PROCESSING TECHNOLOGY

A number of processing techniques are available to the MEMS researcher and fabricator; Table I demonstrates the common processes and techniques available and provides associated application examples.[26] These techniques have their origins in the fields of semiconductor and integrated circuit fabrication and are now prevalent as the micromachining techniques used to create most MEMS devices and structures.[27] The principal advantage to these processes is the reduction in component cost due to batch fabrication. While other techniques are also available, they tend to have limited application, high cost, or low production yields.

These types of processing techniques can be used in virtually any micromachining technology. However, the principal technologies can be resolved into the two types of fabrication techniques known as bulk micromachining and surface micromachining.

Bulk Micromachining

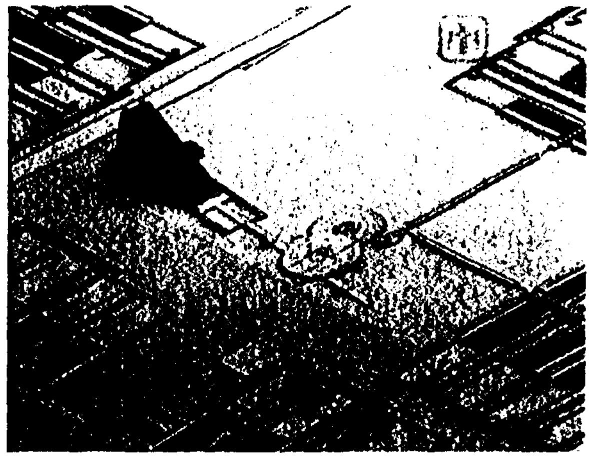
Bulk micromachining involves the etching of silicon surfaces, using either wet or dry techniques and often both. The use of combinations of materials, each having susceptibility to different etchants, allows the construction of elaborate structures such as diaphragms and tunneling tips. Current techniques for the bulk micromachining of silicon diaphragms for pressure sensors have existed for many years, while recent developments in process control have resulted in greater feature definition capabilities. This has consequently led to less-expensive batch fabrication processes and greater process yield per wafer, ultimately driving down the price per device. Through the selection of device substrate (single crystal or polycrystalline) and etchant (isotropic or anisotropic), structures such as diaphragms, beams, bridges, and other suspended and overhanging structures can be created. Further, bonding multiple wafers through a variety of advanced adhesion and bonding techniques provides over-stimuli protection, damping, packaging, and circuitry integration. Figure 1 demonstrates an example of a typical bulk micromachining sequence.

With bulk micromachining techniques, details such as fine corrugations can be achieved to enhance the sensitivity of diaphragms and cantilevers, which, in turn, are capable of measuring very minuscule changes in the operating environment. Depending on configuration, subangstrom-scale measurements have been demonstrated by several investigators.[10,28,29]

Surface Micromachining

Surface micromachining is a class of processes whereby structures are fabricated using additive processing steps on planar surfaces. These processes typically deposit films via a number of techniques on silicon surfaces. By patterning the deposited films, portions of the substrate can be preferentially etched away to release the formed microstructure.

Surface micromachining is typified by the deposition of a layer of silicon, a few micrometers thick, from which beams and other geometries can be built. The challenge to the designer is to take advantage of these thin structures to create machines, using a two-dimensional building process. Figure 2 shows an example of a simple surface micromachining sequence.



A Sandia microengine with an integrated device for positioning microoptics.

Photolithography

Fabricated metallic microstructures are most economically produced using micromolding processes such as photolithography. By exposing an ultraviolet-sensitive material on a planar substrate, mold cavities are formed in thin films and metallized using electroplating. Subsequent etching of the mold material and substrate leaves a free-standing metallic structure, which can then serve as a master die for micromolding complex geometries.

LIGA relies on lithographic patterning, similar to those methods used in surface and bulk micromachining. However, instead of using ultraviolet light to expose the photosensitive layer through a photolithography mask, LIGA uses high-energy x-rays (typical of synchrotron sources) that penetrate to depths of several hundred micrometers in a thick slab of polymethyl methacrylate. The exposed areas are then chemically stripped and metallized using electrodeposition to leave a template made of either nickel or another material. The result may either be used as a structural element or as a master die for a subsequent molding process. Similar to surface micromachining, the LIGA-formed geometries are created by chemically etching away a sacrificial layer, resulting in the final structure on the respective substrate. Because the process can be carried out on the surface of a silicon chip, the technique is also conducive to integrating the control microelectronics and circuitry directly on the same chip. This further reduces part complexity by reducing interconnect problems and decreasing overall device footprint. Some types of MEMS devices that have been successfully manufactured using LIGA are optical devices, accelerometers, turbines, and motors.

MATERIALS DEVELOPMENT

Examples of properties that make materials candidates for selection as MEMS sensors have been reviewed in earlier issues of *JOM*.[30] It is clear that materials that exhibit a strong (typically linear) response to some external stimuli are candidate materials.[31] These are not limited to those conventionally considered, such as piezoelectric, but encompass a range of characteristics to include mechanical, thermal, electrical, magnetic, optical, resistive, acoustic, capacitive, and inductive.

Materials common to microelectronic fabrication, such as silicon, are the materials of choice for MEMS fabricators due to their relatively low cost. However, new materials will ultimately pave the way for further growth in the field. As an example, polymeric composites refer to materials that sense environmental changes by material properties, geometry, mechanical, and electromagnetic responses. These include materials ranging from optically active polymers to multifunctional polymers, piezopolymers, and conducting polymers. Piezopolymers involve the integration of polymers with nanoceramic particles, such as PZT and PLZT, by chemical bonding the nanoparticles as side groups on the polymer backbone. The polymer backbone provides mechanical, electrical, and structural integrity. Nanoceramic particles have active surfaces or functional groups that bond with the polymer chain and provide a piezoelectric response. This class of polymer converts acoustic signals into individual components (two longitudinal and four shear components). The conductive nature of these polymers serves in the same manner as the semiconductor silicon. Sensor and actuators can then be etched or micromachined on these polymeric materials.[32]

CONCLUSIONS

The challenge for industrial and research institutions is to create functional devices that perform an operation other than sensing the environment. The potential for applications is literally limited only by imagination and technological innovation. This challenge must also be weighed by another near-term challenge, which is not necessarily to continue developing more complex devices and "proving the concept," but rather to gain a better understanding of the design and fabrication process of such structures. This will ultimately provide the mechanism that will lead to commercialization of the technology instead of the individual products. In the same manner that microelectronics technology has infiltrated virtually every aspect of daily life, MEMS devices are poised to have the same type of impact.

The integration of sensors, actuators, and computing circuits along with a greater understanding of the unique materials requirements of MEMS will be the key enablers for growth in MEMS usage. The future of MEMS applications may well read like today's science fiction novel. Artificial muscles and skins with implanted MEMS sensors can improve the life of the disabled. Active surfaces on aircraft may monitor the airflow condition and optimize drag and lift by means of arrays of microactuator flaps. Meanwhile, smart structures will continuously monitor the condition of bridges, highways, and seismic structures.

Advancements in this technology are largely restricted by current limits in materials science. While the potential applications far outweigh the number and types of devices currently available, better understanding and familiarity with materials selection, processing, and fabrication technology will enable researchers, and ultimately commercial industries, to meet the grandiose expectation of the field.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support provided by NASA Code Q for the Office of Safety and Mission Assurance Program 323-79, under which this program is funded. Additional acknowledgments are extended to S. Kayali, R. Lawton, S. Cornford, and K. Man of the Jet Propulsion Laboratory for their programmatic and technical contribution to the overall Code Q MEMS program.

References

1. A. van den Berg et al., "MEMS Technology for Space Applications," *Proc. International Conference on Integrated Micro/Nanotechnology for Space Applications* (Netherlands: RPT# NASA-CR-201963, NAS 1.26: 20163 NIPS-96-70364, 1995).
2. B. Benson, A.P. Sage, and G. Cook, "Emerging Technology-Evaluation Methodology: With Application to Micro-Electromechanical Systems," *IEEE Transactions on Engineering Management*, 40 (2) (May 1993) pp. 114–123.
3. G.N. Smit, "Performance Thresholds for Application of MEMS Inertial Sensors in Space," in Ref. 1.
4. J. Carey, "Mighty Mites Hit it Big," *Business Week* (April 26, 1993) pp. 92–94.
5. L. O'Connor, "MEMS: Microelectromechanical Systems," *Mechanical Engineering*, 114 (February 1992), pp. 40–47.
6. K.W. Brendley and R. Steeb, *Military Applications of Microelectromechanical Systems* (Report prepared for the Office of the Secretary of Defense by RAND Corporation, 1993).
7. W.B. Scott, "Micro-Machines Hold Promise for Aerospace," *Aviation Week and Space Technology*, 138 (March 1993), pp. 36–39.
8. H. Guckel, "Silicon Microsensor: Construction, Design and Performance," *Microelectronic Engineering*, 15 (1991), pp. 387–398.
9. J.C. Lyke, M.A. Michalicek, and B.K. Singaraju, "MEMS in Space Systems," in Ref. 1.
10. H.K. Rockstad et al., "A Miniature High-Sensitivity Broad-Band Accelerometer Based on Electron Tunneling Transducers," *Sensors and Acuators*, 43 (1994), p. 107.
11. J. Jerman, "A Minature Fabry-Perot Interferometer with a Corrugated Silicon Diaphragm Support," *IEEE Solid-State Sensor and Actuator Workshop* (New York: IEEE, 1990).
12. H. Guckel et al., "Optical Drive/Sense for High Q Resonsant Microbeams," *Transducers '93* (1993) pp. 686–689.
13. C.B. Williams et al., "Modeling and Testing of a Frictionless Levitated Micromotor," *Sensors and Actuators*, A 61 (1997), p. 469.
14. E.J. Garcia and J.J. Sniegowski, "Surface Micromachined Microengine," *Sensors and Actuators*, A 48 (1995), p. 203.
15. R. Zengerle et al., "A Bidirectional Silicon Micropump," *Sensors and Actuators*, A 50 (1995), p. 81.
16. J.W. Suh et al., "Organic Thermal and Electrostatic Ciliary Microactuator Array for Object Manipulation," *Sensors and Actuators* A 58 (1997), p. 51.
17. S. Ballandras et al, "Microgrippers Fabricated by the LIGA Method," *Sensors and Actuators* A 58 (1997), p. 265.
18. T. Idogaki et al., "Bending and Expanding Motion Actuators," *Sensors and Actuators*, A 54 (1996), p. 760.
19. D. Reynaerts, J. Peirs, and H. Van Brussel, "An Implantable Drug-Delivery System Based on Shape Memory Alloy Micro-Actuation," *Sensors and Actuators*, A 61 (1997), p. 455.
20. A.P. Lee et al., "A Practical Microgripper by Fine Alignment, Eutectic Bonding and SMA Actuation," *Sensors and Actuators*, A 54 (1996), p. 755.
21. M. Rohde and A. Schüssler, "On the Response-Time Behavior of Laser Micromachined NiTi Shape Memory Actuators," *Sensors and Actuators*, A 61 (1997), p. 463.
22. M.C. Wu et al., "Micromachined Free-Space Integrated Micro-Optics," *Sensors and Actuators*, A 50 (1995), p. 127.
23. E. Quandt and K. Seemann, "Fabrication and Simulation of Magnetostrictive Thin-Film Actuators," *Sensors and Actuators*, A 50 (1995), p. 105.
24. R.E. Mihailovich and N.C. MacDonald, "Dissipation Measurements of Vacuum-Operated Single-Crystal Silicon Microresonators," *Sensors and Actuators*, A 50 (1995), p. 199.
25. P. Krause, E. Obermeier, and W. Wehl, "A Micromachined Single-Chip Inkjet Printhead," *Sensors and Actuators*, A 53 (1996), p. 405.
26. J.J. Sniegowski, "Chemical-Mechanical Polishing: Enhancing the Manufacturability of MEMS," *Proc. Micromachining and Microfabrication* (Bellingham, Washington: SPIE 1996), pp. 104–115.
27. D.A. Koester et al., "Advancing MEMS Technology Usage through the MUMPS (Multi-User MEMS Process) Program", in Ref. 1.
28. T.W. Kenny et al., "Micromachined Silicon Tunneling Sensor for Motion Displacement," *Applied Physics Letters*, 58 (1991), p. 100.
29. A.A. Baski, T.R. Albrecht, and C.F. Quate, "Tunneling Accelerometer," *Journal of Microscopy*, 157 (1988), p. 73.
30. A.G. Jackson, S.J.P. Laube, and J. Busbee, "Sensor Principles and Methods for Measuring Physical Properties," *JOM*, 48 (9) (1996), p. 16.
31. W.N. Sharpe, Jr., B. Yuan, and R. Vaidyanathan, "New Test Structures and Techniques for Measurement of Mechanical Properties of MEMS Materials," (Paper presented at SPIE's Symposium on Micromachining and Micromachining and Microfabrication, 1996).
32. V.K Varadan and V.V. Varadan, "Smart Structures, MEMS and Smart Electronics for Aircraft," (Internal work at Pennsylvania State University, 1996), p. 1.

ABOUT THE AUTHORS

John D. Olivas earned his Ph.D. in mechanical engineering and materials science from Rice University in 1996. He is currently a program element manager and staff engineer senior for the Advance Interconnect and Manufacturing Assurance Program at the Jet Propulsion Laboratory.

Stephen R. Bolin earned his M.S. in materials science from Stanford University in 1970. He is currently staff engineer senior and supervisor of the Applications Engineering Group in the Quality Assurance Office at the Jet Propulsion Laboratory.

For more information, contact J.D. Olivas, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Mail Stop 125-161, Pasadena, California 91101-8099; (818) 354-0413; fax (818) 393-5245; e-mail John.D.Olivas@jpl.nasa.gov.